ADVANCES AND TRENDS ON EARTHQUAKE-TRIGGERED LANDSLIDE RESEARCH IN SPAIN

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Abstract: *This work reviews the current situation of earthquake-triggered landslide studies in Spain both from the point of view of regional assessment and site-specific cases. Regional assessments have been undertaken in areas of the Betic Cordillera (South and Southeast Spain): Alcoy Basin, Lorca Basin, Granada Basin and Sierra Nevada Range; and Central Pyrenees (North Spain and Andorra). Specific studies are very scarce, outstanding those related to the Güevéjar landslide (Granada) –triggered by 1755 Lisbon and 1884 Arenas del Rey earthquakes, and to a remarkable rock-slide triggered by 2005 La Paca earthquake (Murcia). Future research lines are appointed, as well as potential applications on Civil Protection and Seismic Hazard Assessment.*

Key words*: Induced landslides, earthquake environmental effects, La Paca, Güevéjar.*

INTRODUCTION

Landslides are one of the most common secondary effects of earthquake vibration. In fact, this phenomenon sometimes produces more victims than damage in buildings itself. Landslides can produce dramatic changes in the landscape and, hence, control the practicality of life-lines in the aftermath of a seismic event (a very recent example is M_w 7.8, 2008 Wenchuan earthquake in China).

The phenomenology of landslides triggered by earthquakes has been thoroughly studied by Keefer (1984, 2002) and Rodríguez et al. (1999). These works concluded that the most common type of earthquake-triggered slope instabilities (landslides s.l.) are rock falls, disrupted soil slides, and rock slides. These types of landslides can be triggered by earthquakes as small as $M{\sim}4$. Additionally, they found a positive correlation between the abundance of landslides and the area affected by them, with earthquake magnitude; although variations due to either specific geological and terrain conditions or seismic parameters are noted.

Earthquake-triggered landslides have also been studied from the point of view of spatial prediction and regional assessment (e.g., Jibson et al., 2000; Luzi and Pergalani, 2000; Romeo, 2000; among others). In these works GIS technologies are intensively used for combining digital geological information with terrain models and seismic input by means of the well known Newmark sliding rigid-block model (Newmark, 1965). Resulting maps have been compared to actual field cases (1994 Northrigde, 1997 Umbria-Marche) drawing satisfactory results and even the proposition of relations between Newmark displacement and probability of failure. Finally, earthquake triggered landslides have also been the subject of site-specific studies. Few works have been devoted to verifying the goodness of the Newmark method in the field in the aftermath of an event (e.g., Wilson and Keefer, 1983). These authors concluded that this method draws reasonable good predictions of coseismic downward slope displacement –provided certain geotechnical conditions are fulfilled. Another set of works are focused on analysing the hypothetical seismic origin of particular landslides associated either to a known historical earthquake (e.g., Jibson and Keefer, 1993) or to paleoseismic events (cf. Jibson, 1996). Actually, when written records are not available, reliable cause-and-effect relationships between specific earthquakes and landslides are difficult to demonstrate. In these cases it is necessary to dismiss the influence of other triggering factors (e.g., intense rainfall, erosion) by means of slope stability back-analysis.

Slope instabilities are reported recurrently in the chronicles of pre-instrumental earthquakes in Spain. It is common to come across short phrases as (Fig. 1): "*…una hendidura de siete leguas se abrió a través de las montañas de Bas…*" (Vielha, 1428), "*…en el sacudimiento de los montes se han juntado dos peñascos, y hay que buscar el camino por otro sitio...*" (Almería, 1522), "*…el monte Cantagallet se abrió en distancia de legua y media…*" (Alcoy, 1620); "*…la sierra de los moros se abrió en dos partes…*" (Alboloduy, 1713), "*…se hundieron unas tierras entre Lorca y Totana…*" (Lorca, 1818); etc. In some cases these descriptions could be related to surface faulting. In fact, Spanish earthquake chronicles are still poor researched from the point of view of environmental earthquake effects (EEE). Most of the research has been devoted to assigning macroseismic intensities based on building damage and social impact. Fortunately, INQUA is currently promoting efforts on that direction, being good examples the EEE international database and the Environmental Seismic Scale (ESI) (Michetti et al., 2007).

Nevertheless the lack of research, Spain has a few significant cases of earthquake triggered landslides. From the historical period the most interesting one is the Güevéjar landslide in Granada (Sanz, 1997; Jimenez Pintor and Azor, 2006), which is discussed later. Respecting to the instrumental period, the most dramatic case may be the river Beiro landslide (Granada). This landslide was triggered by the 1956 Albolote-Atarfe earthquake (M_L=5.0, I_{MSK}=VIII) killing 5 people (IAG, 2009). The earthquake also produced rock-falls around Sierra Elvira. More recently, three seismic series all located in the Murcia Region: 1999 Mula (m_{bLg}=4.8, I_{EMS}=VI), 2002 Bullas (m_{bLg}=5.0, I_{EMS}=V) and 2005 La Paca (m_{bLg}=4.7, I_{EMS}=VI–VII), have produced interesting case-study examples of rock-falls and rock-slides. The 2005 La Paca case is discussed later.

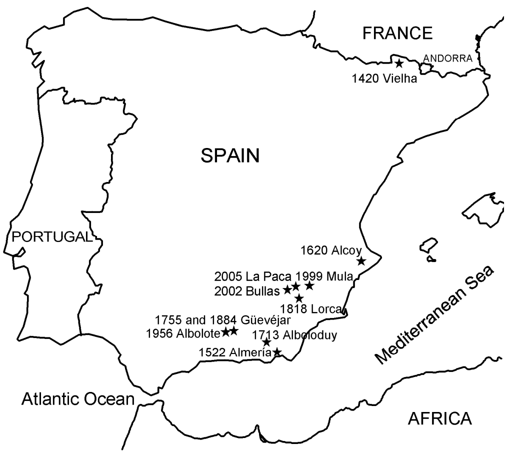

Fig. 1: Location of the earthquakes and towns cited in the text.

REGIONAL ASSESSMENT OF EARTHQUAKE-TRIGGERED LANDSLIDE HAZARD IN SPAIN

Even though in Spain a great number of studies dealing with regional landslide assessment exist, those especifically focussed on analysing the seismic factor are very few: García-Mayordomo (1998, 1999), Mulas et al. (2001 y 2003), Coral Moncayo (2002), Figueras et al. (2005), Delgado et al. (2006), Rodríguez-Peces (2008) and Rodríguez-Peces et al. (2008, 2009a,b). All these works are based on the Newmark method and most of them make use of geospatial information by means of a geographical information system (Idrissi, ArcGIS).

García-Mayordomo (1998, 1999) analysed the stability of two particular slope models widely distributed accross the Alcoy Basin (Alicante, Eastern External Betics), finding that critical accelerations as low as 0.03 g to 0.04 g could potentially trigger landslides. In the same area, Delgado et al. (2006), after modelling the natural variability of geothecnical parameters by means of Montecarlo analysis, obtained a set of maps in terms of the probability associated to a critical acceleration lower than 0.1 g for dry and saturated conditions. He found out a very good correlation between high probability areas and the distribution of actual known cases triggered by the 1620 Alcoy (I_{MSK}=VIII) and 1945 Onteniente (m_{bLg}=4.0, I_{MSK}=VII) earthquakes. From both García-Mayordomo (1999) and Delgado et al. (2006) studies is drawn that earthquake-triggered landslides in the Alcoy Basin appear to be a frequent and repeated phenomena.

Coral Moncayo (2002) and Figueras et al. (2005) works, performed in Andorra (Pyrenees), are particularly outstanding for assessing earthquake-triggered landslide hazard in terms of probability of failure as a function of Newmark displacement –although this is eventually done using Jibson (2000) equation derived from Northridge earthquake data. Newmark displacement is calculated from empirical relationships with Arias Intensity as well as from real accelerograms consistent with the 475-year return period in the area (PGA~0.1 g), and assuming a critical acceleration of 0.01 g. They finally concluded that probability of failure is only significant for slopes greater than 40°.

Mulas et al. (2001 y 2003) works in the valleys of Gállego and Caldarés rivers (central Pyrenees) deal with designing a specific methodology for the quantitative assessment of slope instability levels against the seismic phenomena. Instability levels are derived from a matrix that combines discrete values of a variable dependant on aseismic factors (slope, lithology,…) with another variable dependant on seismic soil response; which is also a function of macroseismic intensity. For intensity levels between VI y VIII (presumably related to the 500-year return period), the authors found out that the areas with the highest levels of instability coincided with the higher parts of the valleys, in contrast with the actually known aseismic instabilities location.

Finally, Rodríguez-Peces, 2008 and Rodríguez-Peces et al. (2008, 2009a,b) studies in the Lorca Basin (Murcia, Eastern Betics) and Granada Basin and Sierra Nevada (Central Betics), are focussed on obtaining Newmark displacement maps for seismic scenarios of engineering significance –e.g., related to certain return periods or to the occurrence of specific earthquakes. First, maps in terms of peak ground acceleration on rock (PGA) related to each scenario are obtained. Then, PGA is modified to account for soil and topographic amplification. Next, critical accelerations are calculated and combined with modified PGA to obtain Newmark displacements for each specific scenario by means of using Jibson's (2007) equation. Finally, the obtained maps are compared with the distribution of slope instabilities and particularly with those few known cases of triggering (Fig. 2). The authors found a good correlation between known instabilities and areas showing Newmark displacement values, particularly for the deterministic scenarios. They conclude suggesting that future instabilities in the Lorca and Granada basin would be fundamentally rock-falls, rock-slides and rock-avalanches, and that only the occurrence of large magnitude earthquake (M_w≥6.0) could possibly produce larger and deeper instabilities or affect extensive areas.

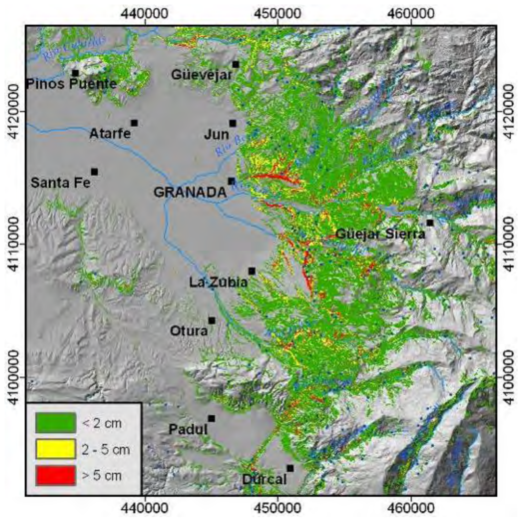

Fig. 2: Newmark displacement map of eastern Granada Basin for a seismic scenario considering the complete rupture of the Granada Fault. Blue dots locate known slope instabilities (modified from Rodríguez-Peces, 2008).

ANALYSIS OF SPECIFIC EARTHQUAKE-TRIGGERED LANDSLIDE CASES

Site-specific studies focused on analysing the dynamic stability of particular slopes known to have failed during an earthquake are very scarce in Spain. At this respect, it is important to clarify that a different kind of studies are those included in civil engineering projects aimed at guaranteeing the stability against earthquakes of modified slopes or man-made earth structures, which are not discussed in this abstract.

From the Spanish seismic historical period (prior to 1920) the most interesting case is the Güevéjar landslide in Granada (Sanz, 1997; Jiménez Pintor and Azor, 2006). This is a large-size paleolandslide (approx. 200 ha, $60 \bullet 10^6$ m3) that was reactivated both in the 1755 Lisbon and 1884 Arenas del Rey earthquakes. It is interesting to note that the epicentre of the Lisbon earthquake is located more than 500 km away from Güevéjar (Martínez Solares and López Arroyo, 2004), and that it was felt with I_{MSK} VI at the village –even though it was badly damaged by the landslide. Similarly, the 1884 Arenas del Rey earthquake (M~6.5) –which was located 50 km far and was felt at the site with I_{MSK} VII, reactivated the landslide provoking the ruin of the village and its definitive move to a safer location. Güevéjar landslide arises many interesting questions: how old is the landslide? Can any other seismic events be inferred and dated from landslide history? What are the factors controlling landslide reactivation from strong ground motion from far sources? How important are site effects? Could be the landslide be reactivated today? etc. The answer to any of these questions will be necessarily based on a geomechanical model of the slope built from geotechnical data and geophysical observations –information so far not available. Rodríguez-Peces et al. (this volume) are starting research on this landslide.

Respecting to instrumental earthquakes, Rodríguez-Peces et al. (2009a and c) have studied in detail 2005 La Paca rock-slide (Fig. 3). A field survey using a terrestrial laser scan was carried out to obtain a high resolution digital elevation model (DEM). In addition, the *Joint Roughness Coefficient* (JRC) and the *Joint Compressive Strength* (JCS) parameters were measured on the failure plane. Subsequently, a stability back-analysis was performed considering a slide failure mechanism. A static safety factor of 1.09, a critical acceleration of 0.09 g and a Newmark displacement of 0.18 cm were calculated. Furthermore, the authors compared these parameters with the ones that could be obtained by GIS considering regional (25 x 25 m) and local scale (2.5 x 2.5 m) DEMs, as well as geotechnical data from bibliography. They concluded that results from regional DEMs can provide not reliable results, while the use of local MDT appears to provide results very similar to site-specific analysis.

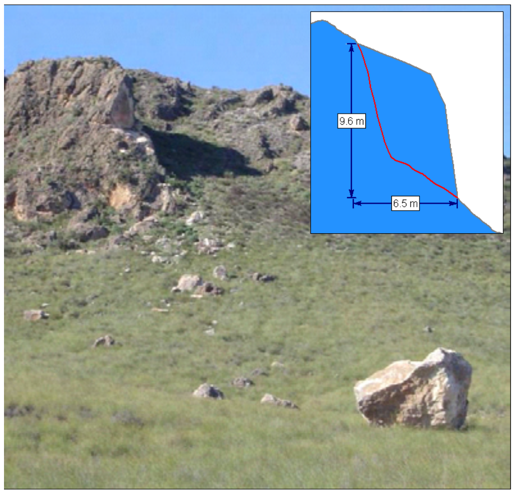

Fig. 3: Rock-slide and subsequent rock-fall associated to 2005 La Paca earthquake (modified from Rodríguez-Peces et al. 2009a and c)

RESEARCH LINES AND TRENDS

A first research line would consist in carrying on detailed studies of slope instabilities univocally known to be associated to recent instrumental earthquakes (e.g., Bullas 2002, La Paca 2005) or events to come. In this cases safety static factors and critical acceleration can be calculated based on field data. In addition, provided that the magnitude and distance-to-the-site of the earthquake are precisely known, Newmark displacements could be calculated from real time-histories. Results from this type of studies can be used to devise relationships between Newmark displacement, type of instability, probability of failure, etc. and be used to calibrate regional scale maps obtained for specific seismic scenarios. Ideally, a probability of failure distribution could eventually be drawn for the particular geological conditions of different Spanish regions.

A second research line would first accomplish a detailed study of historical earthquake chronicles with the aim of identify and locate in the field slope instabilities (or environmental earthquake effects in general) related to the event. Once the most evident cases are identified, a particular study for each one it would proceed. An approach similar to the one described above can be followed, but in this case the main achievement would be to constraint the size and distance-to-the-site of the old earthquake. In uncertain cases, as well as in very old earthquakes, absolute dating must be necessarily applied.

APPLICATIONS OF THE INVESTIGATIONS

The results of earthquake-triggered landslides research are potentially very interesting for a variety of issues in seismic hazard: evaluation of site and topographic effects, complementation of strong ground motion observations, assessment of the size and level of ground shaking related to particular historical earthquakes or old instrumental ones, etc.

In relation to Civil Protection, maps in terms of critical acceleration –or in terms of Newmark displacement properly calibrated with site specific studies, could be used to simulate the distribution and severity of slope instabilities in relation to a particular seismic scenario in a particular county. These simulations would permit to assess the interruption of lifelines (roads, electric lines, gas pipes, water channels,…) in case of earthquake and, hence, to improve emergency plans in the aftermath of an event.

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